

DBCP, EDB, and TCP Contamination of Ground Water in Hawaii

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ABSTRACT

In recent years, several pesticide-related contaminants have been detected in the ground waters of the State of Hawaii. Two soil fumigants previously used by pineapple growers, 1,2-dibromo-3-chloropropane (DBCP) and 1,2-dibromoethane or ethylene dibromide (EDB), have been detected in several wells on Oahu and Maui. An impurity of the soil fumigant DD, 1,2,3-trichloropropane (TCP), also has been detected in a number of wells. DBCP, EDB, and TCP are of particular concern to State public health officials due to known and possible unknown health effects associated with these compounds.

The locations of the contaminated well sites on Oahu appear to be correlated with the areas of past and present pineapple cultivation when the ambient ground-water flow pattern is taken into consideration. In addition, several large fuel pipeline leaks are located in the vicinity of the EDB contamination. In general, TCP contamination is more widespread than either DBCP or EDB contamination. TCP levels appear to be declining in Oahu water wells while EDB levels in the contaminated portion of southern Oahu appear to be increasing. The direction of temporal trends in DBCP concentration at present varies according to site.

INTRODUCTION

Although pesticides minimize agricultural losses, the chemicals can pose a serious public health threat if they eventually reach and contaminate ground water. In recent years, this threat has become most evident as increasing numbers of pesticides have been discovered in the nation's ground-water sources. Since 1979 for instance, the nematicide, 1,2-dibromo-3-chloropropane (DBCP), has been discovered in the ground waters of Arizona, California, Hawaii, Maryland, and South Carolina. In 1984 another nematicide, 1,2-dibromoethane or ethylene dibromide (EDB), was reported to be found in the ground waters of California, Florida, Georgia, and South Carolina (Cohen *et al.*, 1984). By 1986, ground-water con-

tamination as a result of agricultural use of EDB was known to exist in Arizona, Connecticut, Massachusetts, and Washington as well (Cohen *et al.*, 1986). The discovery of 1,2,3-trichloropropane (TCP) in the ground waters of California and Hawaii (Cohen *et al.*, 1986) is further evidence of the contamination potential of agricultural chemicals. Some of the properties of DBCP, EDB, and TCP are presented in Table 1.

Over the past several decades, pesticides have been used extensively by the pineapple industry in Hawaii. In recent years, various pesticide-related contaminants have been detected in the basal ground waters of several of the State's aquifers. DBCP and EDB, two soil fumigants previously used by pineapple growers, have been discovered in wells on Oahu and Maui (Figure 1). On Oahu, 10 wells were closed by the Hawaii State Department of Health (DOH) because of DBCP or EDB contamination. DBCP also has been found in one well on Kauai. A third contaminant, TCP, an impurity of the soil fumigant DD (a dichloropropane-dichloropropene mixture), has been detected in wells on Oahu and Maui and in the well on Kauai also contaminated with DBCP. DBCP, EDB, and TCP contaminations have been of particular concern because of the associated health effects, both known and unknown (Anderson, 1986). The U.S. Environmental Protection Agency recently proposed recommended maximum contaminant levels (RMCLs) of 0.0 for both DBCP and EDB (American Water Works Association, 1985). The Pearl Harbor aquifer, which is the primary source

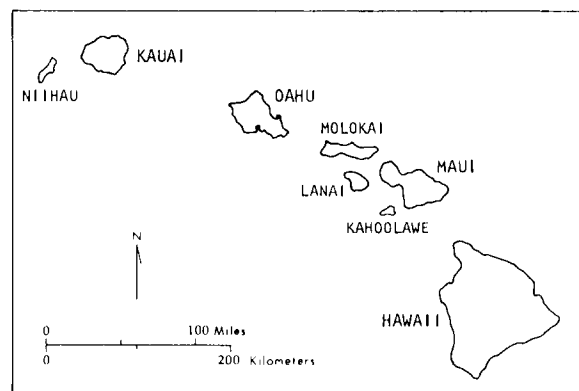


Fig. 1. Location map of Hawaii.

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Table 1. Chemical Properties of DBCP, EDB, and TCP

| | <i>DBCP</i> | <i>EDB</i> | <i>TCP</i> |
|----------------------------|---|-------------------------------------|---|
| Formula | $\text{BrCH}_2\text{CHBrCH}_2\text{Cl}$ | $\text{BrCH}_2\text{CH}_2\text{Br}$ | $\text{CH}_2\text{ClCHClCH}_2\text{Cl}$ |
| Boiling point | 196°C | 132°C | 156°C |
| Specific gravity | 2.08 at 20°C | 2.17 at 25°C | 1.39 at 20°C* |
| Solubility in water (mg/l) | 1230 at 20°C | 3370 at 20°C | — |
| Vapor pressure (mm Hg) | 0.58 at 20°C | 11.0 at 25°C | 3.4 at 20°C |

* Ratio of the density of TCP at 20°C to the density of water at 4°C.

Sources: Munnecke and Van Gundy, 1979; Spencer, 1982; U.S. Department of Health and Human Services and U.S. Department of Labor, 1978; U.S. Environmental Protection Agency, 1980; Worthing, 1979.

of potable water for Honolulu and the State's most important ground-water resource (Mink, 1980), has shown detectable levels of all three contaminants in some wells. Attention is, therefore, focused on the central Oahu area. An intensive effort is currently underway to determine the extent, movement, and probable persistence of contamination in this region (Lau, 1985). The objective of this paper is to use available ground-water quality data to examine spatial and temporal patterns of DBCP, EDB, and TCP contamination in the central Oahu area and to identify their possible sources.

DISCOVERY OF CONTAMINATION IN HAWAII

On April 7, 1977, an incident occurred which foreshadowed Hawaii's current ground-water contamination problem. On that day, a spill of approximately 1.9 m³ (500 gal) of EDB occurred within 18 m (60 ft) of the Del Monte Corporation's water-supply well at Kunia on Oahu (Figure 2). Although laboratory analyses performed on well water sampled approximately one week after the spill failed to detect EDB at the 500-ng/l (nanograms per liter) limit of detection, the spill focused

attention for the first time on the possibility of pesticide contamination of ground water in the State of Hawaii.

In response to the discovery of DBCP contamination in California wells, the U.S. Environmental Protection Agency (EPA) in May 1979 asked five states in which DBCP was used (Arizona, Florida, Georgia, Hawaii, and South Carolina) to test their water supplies for the compound. As a result, the State of Hawaii initiated its first DBCP sampling program in June 1979. Water samples were taken from 16 sites on Oahu, Maui, Molokai, and Lanai, chosen on the basis of proximity to pineapple fields with a history of DBCP applications. Initial analyses by two laboratories (Hawaii State Department of Health and California State Department of Food and Agriculture) were negative at all 16 sites. At the time of the analyses, the DOH laboratory had a detection limit of 130 ng/l for DBCP.

Although neither DBCP nor EDB were detected as a result of the aforementioned sampling efforts, these chemicals were subsequently discovered in the ground waters of Hawaii as equipment sensitivity improved, sampling frequency increased, and areal sampling coverage expanded. On the island of Oahu, several laboratories confirmed the presence of DBCP and EDB in the Del Monte Kunia Well in April 1980. DBCP concentrations ranged from 500 to 11,000 ng/l, while EDB levels ranged from 92,000 to 300,000 ng/l. The DOH ordered the well closed as a result of the contaminants found (Figure 2). From 1982 to 1983, 10 potable water wells on the island of Oahu were closed due to DBCP or EDB contamination (Figure 2). The maximum concentrations of the compounds DBCP, EDB, and TCP detected at the closed sites are presented in Table 2.

Analyses for TCP by local laboratories were not performed until September 1983. These initial analyses revealed TCP contamination at all but one

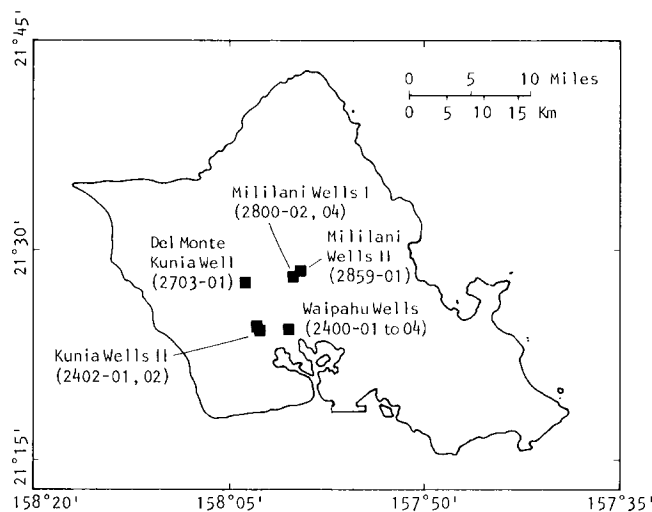


Fig. 2. Closed well sites on Oahu, Hawaii.

of the previously closed well sites on Oahu (no test for TCP was done at the Del Monte Kunia Well). In addition, water samples taken from several other wells in central Oahu were found to have TCP.

Concentrations of TCP on the order of 2000 ng/l have been measured at well sites on Oahu. These concentrations contrast sharply with the 20 to 100 ng/l of DBCP or EDB typically found in Oahu wells. There are no present standards pertaining to the allowable amounts of DBCP, EDB, or TCP in drinking water in the State of Hawaii. The DOH does, however, have a policy of closing any well with confirmed quantitated amounts of EDB or DBCP. (Present detection limits used by three local laboratories in the State of Hawaii for EDB and DBCP are 20 ng/l.) Yet if no other water sources are available, the Department of Health will, of necessity, allow the source to be used. The DOH does not have an action limit for TCP, based on the assumed lesser risk associated with its consumption. Generally, the DOH considers EDB to be the most toxic of the three, followed by DBCP and then TCP.

SITE

Oahu, the home of 80% of Hawaii's one million residents, is still the site of extensive pineapple cultivation. It is not surprising, therefore, that the State's most critical pesticide-related ground-water contamination problems are found on Oahu, particularly in the central portion of the island (Figure 3) which encompasses the Pearl Harbor aquifer and all of the present pineapple-growing areas. Because more potable-water sources are affected, and a greater abundance of data exist for Oahu than for the other islands, it is appropriate to begin the study of Hawaii's ground-water contamination there.

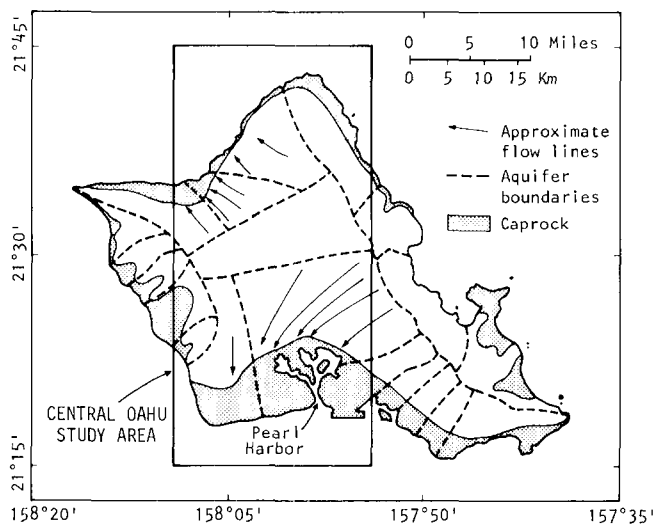


Fig. 3. Aquifer and caprock boundaries for Oahu, Hawaii (adapted from Eyre, 1983; Mink and Sumida, 1984; Rosenau *et al.*, 1971; and Takasaki, 1977).

Geology and Hydrology

The island of Oahu is formed primarily from the lavas of the Koolau and Waianae shield volcanoes. The Koolau dome and the lower portion of the Waianae dome consist mainly of thin basaltic flows [generally less than 3 m (10 ft) in thickness]. A coastal plain of poorly permeable terrestrial and marine sediments acts as a caprock restraining the seaward movement of fresh ground waters (Figure 3). The basal ground water of Oahu consists of a lens of fresh water floating on sea water. The permeability of the unweathered rock that forms the basal aquifers of Oahu is generally high, with hydraulic conductivities on the order of 0.004 m/s (1000 ft/day). Aquifer boundaries consist of dike formations in volcanic rift zones and sedimentary deposits which extend inland

Table 2. Maximum Detected Contaminant Levels in Closed Wells on Oahu

| Site Name | Maximum concentrations (ng/l) and sample dates | | | | | |
|--------------------------|--|----------|--------|----------|------|----------|
| | DBCP | Date | EDB | Date | TCP | Date |
| Del Monte Kunia Well | 14000 | 5- 5-80 | 300000 | 4-24-80 | # | # |
| Kunia Wells II Pump 1 | 38 | 11- 8-83 | — | — | 1050 | 10-13-83 |
| Kunia Wells II Pump 2 | 26 | 7-17-84 | — | — | 1100 | 10-14-83 |
| Mililani Wells I Pump 2 | 42 | 1-16-84 | *20 | 9-12-83 | 1820 | 8-30-83 |
| Mililani Wells I Pump 4 | 51 | 2-14-84 | *25 | 9-12-83 | 2500 | 7-24-84 |
| Mililani Wells II Pump 5 | 97 | 9-13-82 | *20 | 11-18-83 | 2800 | 3- 6-84 |
| Waipahu Wells Pump 1 | — | — | 58 | 11- 8-83 | 320 | 7- 3-84 |
| Waipahu Wells Pump 2 | — | — | 75 | 11- 8-83 | 300 | 11- 8-83 |
| Waipahu Wells Pump 3 | — | — | 100 | 7- 3-84 | 350 | 7- 3-84 |
| Waipahu Wells Pump 4 | +2 | 9-27-83 | 190 | 11- 8-83 | 300 | 10-27-83 |

No test.

— No positive quantitated results.

* Concurrent and subsequent tests failed to verify EDB in Mililani Wells.

+ Analysis performed by Stoner Laboratory, Santa Clara, California, at a detection limit of 1 ng/l.

from the coastal caprock, filling ancient valleys. Rainfall is the principal source of recharge to the basal waters. Recharge also occurs as a result of inflow from dike compartments at higher elevations, inflow from streams, and deep percolation of irrigation return water. Discharge from the aquifers occurs as a result of well withdrawals and the natural discharge of fresh water along the margins of and through leaks in the caprock. In the absence of external influences such as pumping, the ambient ground-water flow direction is from areas of high recharge along the crests of the Koolau and Waianae ranges toward the coast. The general flow patterns for selected aquifers within the study area are presented in Figure 3.

Land Use

Land use is a critical factor affecting recharge, which in turn can affect the leaching of pesticide residues. Leaching of pesticide residues may be accelerated as a result of high percolation rates in agricultural areas. On agricultural lands, irrigation, especially of sugarcane, contributes significantly to recharge. Because of the very low rate of evapotranspiration associated with pineapple crops (Ekern, 1965), recharge in areas of pineapple cultivation in central Oahu may be as much as four to five times the rate for areas of natural vegetation (Giambelluca, 1986). Areas of past and present pineapple cultivation (1940-1985) are shown in Figure 4. Some of these areas were converted from pineapple cultivation to sugarcane cultivation, which would tend to increase the leaching of pesticide residues due to the large amount of water used for sugarcane irrigation.

Plantation Practices

Two pineapple growers on the island of Oahu are Dole Company and Del Monte Corporation. A third company, Libby, was involved with pineapple cultivation on Oahu prior to the early 1960s. Fumigant usage by the different plantations varied over time. The general plantation practices with regard to soil fumigation are outlined below.

1,2-Dibromo-3-Chloropropane (DBCP)

DBCP is a soil fumigant introduced in 1955 by the Dow Chemical Company and the Shell Development Company. It was used in Hawaii to control the particularly hardy reniform nematodes that attack the roots of pineapple crops. DBCP was injected into the soil once every three to five years at a depth of approximately 0.20 to 0.25 m (8 to 10 in.) beneath a polyethylene film prior to planting at a rate of 28.1 to 37.4 l/ha (3 to 4 gal/

acre) (active). It was generally applied with another fumigant, such as DD or Telone (predominantly a 1,3-dichloropropene mixture). The volumetric application ratio of DBCP to DD or Telone was about 1 to 10 (Yim and Dugan, 1975).

DBCP was first used on a significant commercial basis by Dole Company on Oahu in 1959 (L. Wong, pers. commun., 1986). Dole Company phased out the use of DBCP in the 1977 planting season while Del Monte Corporation did not use DBCP on Oahu except on an experimental basis (Department of Agriculture, 1983).

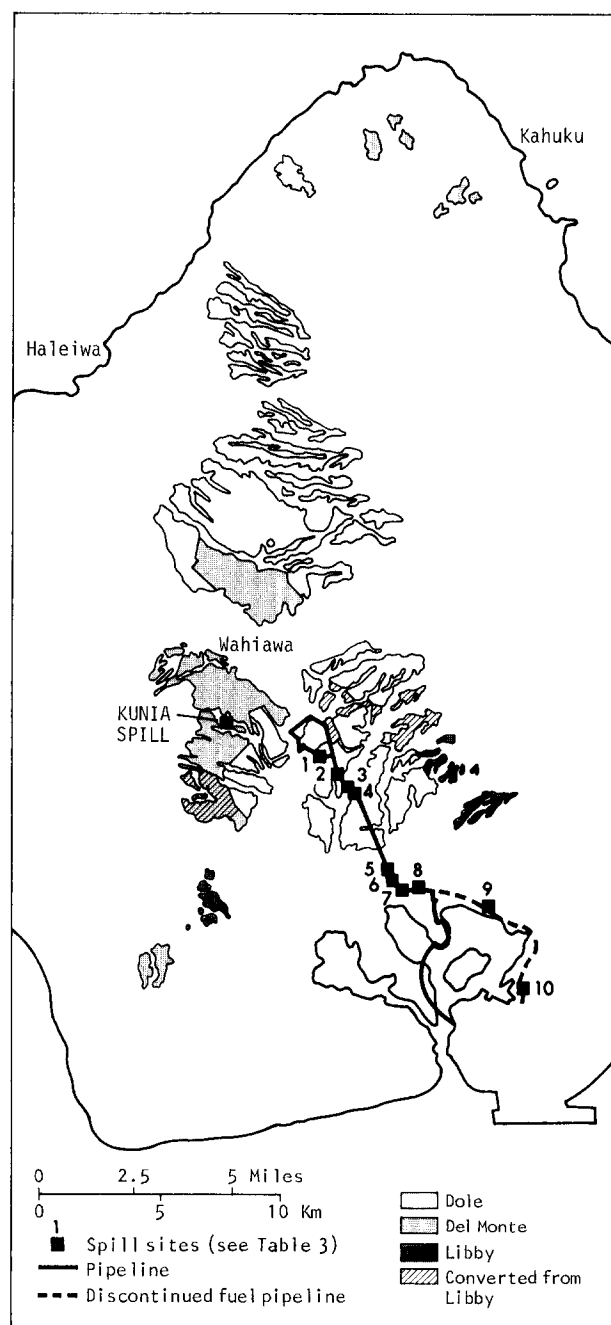


Fig. 4. Spill sites and areas previously and presently under pineapple cultivation, central Oahu, Hawaii (pipeline spill sites adapted from Engineering-Science, 1984).

1,2-Dibromoethane (EDB)

EDB was used in a tetraethyl lead mixture added to aviation fuels (Lau, 1985). EDB was also used as a fumigant which was introduced by the Dow Chemical Company in 1946 (Worthing, 1979). The Environmental Protection Agency reported in 1983 that over 9.07×10^6 kg (20×10^6 lb) of ethylene dibromide were being used in this country every year with soil fumigation accounting for 90% of the volume used (U.S. EPA, 1983). Although EDB was used as a quarantine fumigant for papayas in Hawaii, its major use in the State was for the soil fumigation of pineapple fields to control nematodes. As a soil fumigant for pineapple fields, EDB was injected into the ground once every three to five years at a depth of approximately 0.20 to 0.25 m (8 to 10 in.) prior to planting at a rate of 93.6 to 112.3 l/ha (10 to 12 gal/acre) (active). A polyethylene film was placed over the soil at the time of application to retain the volatile fumigant and thereby improve nematode control. The film also helped to retain moisture and increase soil temperature which improved early plant growth. Planting occurred 48 hours or more after fumigation (Department of Agriculture, 1983).

On Oahu, EDB was the primary soil fumigant of Del Monte Corporation for approximately 35 years prior to the EPA notice of cancellation and emergency suspension of registrations in September 1983. Dole Company only began using EDB on Oahu on a significant commercial scale in 1978 after it phased out the use of DBCP in 1977 (Department of Agriculture, 1983). Dole Company did use EDB on a limited basis (primarily post-plant applications) between 1948 and 1959 (L. Wong, pers. commun., 1986). By the terms of the cancellation order, the use of EDB on pineapple fields in Hawaii was allowed until September 1, 1984. Dole Company chose not to use up its remaining stocks and discontinued use of EDB at the time of the order. *The Honolulu Star-Bulletin* (February 13, 1984) reported that Del Monte Corporation continued use of EDB until its remaining supply was depleted by the end of 1983.

1,2,3-Trichloropropane (TCP)

TCP is used as a paint and varnish remover, a solvent, and a degreasing agent (U.S. EPA, 1980). It also occurred as an impurity during the manufacturing process of the Shell Chemical Company product DD which was introduced in 1942. The first use of DD as a soil fumigant was described in 1943 (Worthing, 1979). Estimates of the amount of trichloropropanes in the DD mixture vary from

0.4% by weight (Department of Agriculture, 1984) to 6 to 7% by weight (Carter, 1954). The actual amount of trichloropropanes in the mixture, however, may have greatly deviated from these values at times.

Shell DD became the primary soil fumigant of Dole Company in 1948 when Del Monte Corporation selected EDB as its primary fumigant (L. Wong, pers. commun., 1986). Shell DD was later used as a pre-plant nematicide (every three to five years) in conjunction with DBCP by Dole Company on Oahu. Where the reniform nematode was not present, DD (or Telone) was applied alone at the rate of 370 to 560 l/ha (40 to 60 gal/acre) (Yim and Dugan, 1975). It is also believed that Libby used a DD formulation with a high TCP content on its fields. Although records are not available to determine when DD was first used on a commercial basis by Libby on Oahu, DD was most likely first used in the late 1940s. *The Honolulu Advertiser* (October 6, 1983) reported that DD has not been used on pineapple fields on Oahu since 1977.

LABORATORY PROCEDURES

A number of local and out-of-state laboratories performed analyses on water samples taken from sites within the study area. Different laboratories utilized different analytical procedures to measure DBCP, EDB, and TCP. In addition, individual laboratories changed their practices during the period of study as new equipment and techniques became available. Of the six local laboratories which performed analyses pertinent to this paper, five employed some form of co-distillation using benzene or hexane as a solvent for extraction. Water sample volumes used ranged from 250 to 600 ml. These five laboratories utilized a gas chromatograph and ^{63}Ni electron capture detector for analysis. The operating conditions (oven, inlet, and detector temperatures; carrier gas type and flow rate; and injection volumes) and equipment (column type and packing), however, varied among the laboratories. The remaining local laboratory utilized a purge and trap technique with detection and quantification by gas chromatography and mass spectrometry. The bulk of the data obtained was from analyses by local laboratories. The out-of-state laboratories utilized either co-distillation/gas chromatography or purge and trap/gas chromatography/mass spectrometry.

The nonuniformity of laboratory procedures utilized leads to variability of analytical results.

Analyses performed on the same water sample by different laboratories have often produced significantly different results. On one occasion, for instance, split sample analyses by nine different laboratories of water sampled from Waipahu Wells Pump 4 resulted in concentrations of EDB ranging from 38.2 to 190 ng/l. (Variability in sampling and storage procedures also may have contributed to the lack of reproducibility.) Changes in equipment or solvent used by a laboratory also may lead to variability.

DISCUSSION

Spatial Distribution of Contamination

Water quality data compiled by the Water Resources Research Center (WRRC) (Oki and Giambelluca, 1985) were utilized to determine the

extent of the contamination in central Oahu aquifers. Additional results from recent analyses performed by the University of Hawaii (Lau, 1985) were utilized to supplement the existing WRRC Data Base. Separate maps were drawn to depict the spatial distributions of DBCP, EDB, and TCP contamination (Figures 5, 6, and 7, respectively). On each map, all well sites tested for the particular compound of interest are shown. Well sites with at least one positive quantitated analytical result are identified.

Well and spring sites tested for DBCP, EDB, and TCP contamination are respectively presented in Figures 5, 6, and 7. The locations of the contaminated well sites appear to correspond with the areas of past and present pineapple cultivation when the ambient ground-water flow patterns

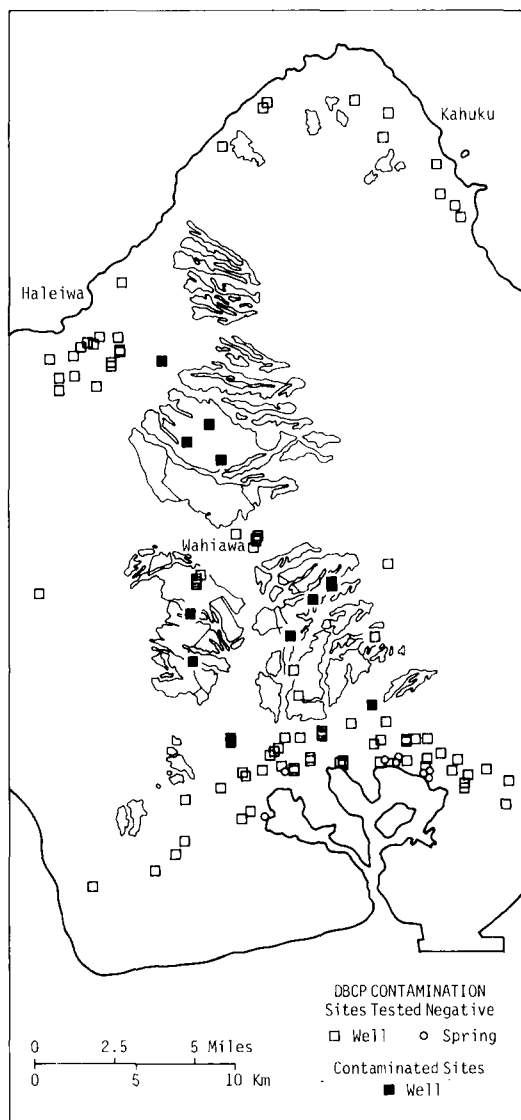


Fig. 5. Well and spring sites tested for DBCP contamination in relation to areas of pineapple cultivation, central Oahu, Hawaii.

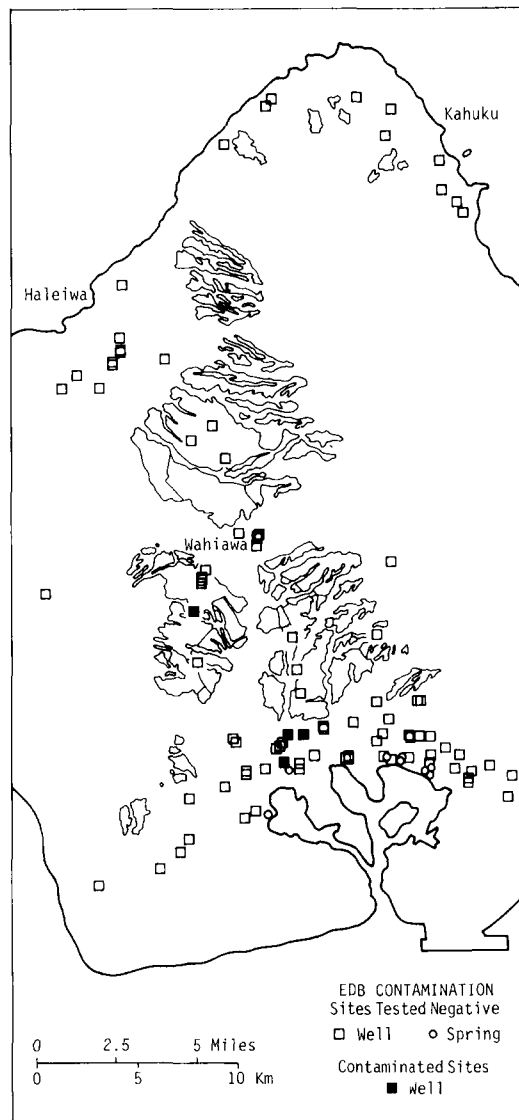


Fig. 6. Well and spring sites tested for EDB contamination in relation to areas of pineapple cultivation, central Oahu, Hawaii.

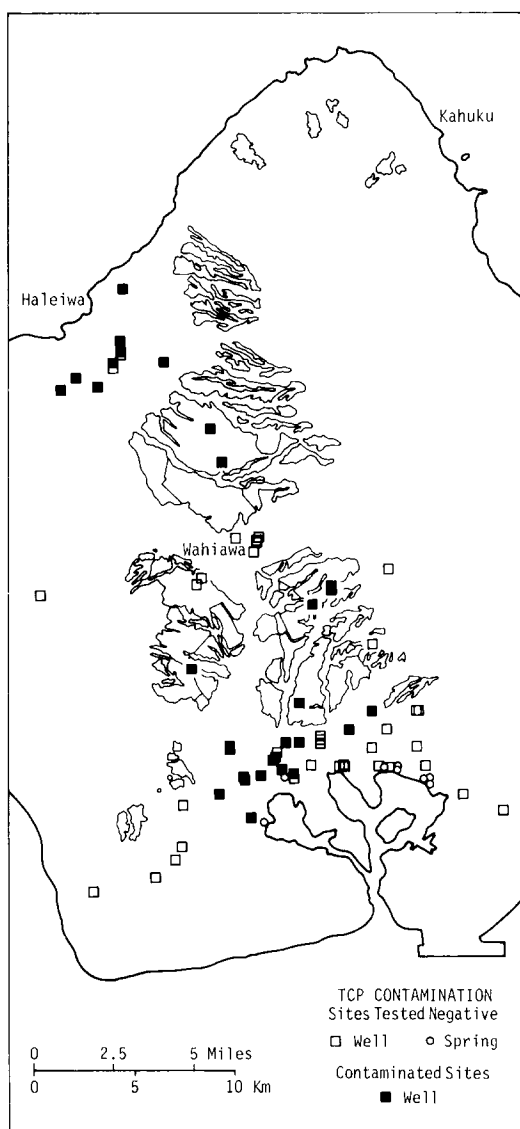


Fig. 7. Well and spring sites tested for TCP contamination in relation to areas of pineapple cultivation, central Oahu, Hawaii.

(Figure 3) are taken into consideration. That is, the contaminated well sites are located directly within or hydraulically downgradient of areas of pineapple cultivation. (The contamination cannot be linked to sugarcane, the only other major crop grown in the area, since the nematicides DBCP, EDB, and DD were not used to fumigate sugarcane fields.) The Del Monte Kunia Well is not downgradient from any fields which received regular applications of DBCP. DBCP contamination at that well site was originally attributed to the single spill of EDB (which contained DBCP as an impurity) in April 1977. A subsequent investigation, however, revealed that DBCP (used experimentally) and EDB spillage which occurred during mixing and transfer operations at a nearby chemical storage area was the primary source of contamination (Mink, 1981). All other sites contaminated with

either DBCP or TCP are within or hydraulically downgradient from fields which received applications of DBCP or DD. Detection of EDB contamination has thus far been confined to a small area north of Pearl Harbor [positive tests for EDB at Mililani Wells I and II (Table 2) have been questioned by State health officials, and concurrent and subsequent tests have failed to verify the presence of EDB in Mililani Wells]. The EDB contamination may be the result of soil fumigation on upgradient Dole fields. However, because the EDB-contaminated area is close to the sites of several documented pipeline leaks of aviation fuels (Figure 4 and Table 3), the source of this contamination cannot be identified with certainty. Possible undocumented spills and leaks of petroleum products also may have served as sources of EDB contamination. Furthermore, pesticide storage and transfer sites at unknown locations could have been point sources of DBCP, EDB, or TCP contamination.

Based on discoveries to date, TCP contamination is more widespread and exists at higher concentrations in the ground water than either DBCP or EDB. This may suggest that TCP is more persistent and that a greater fraction of the applied quantity survives and is transported to the water table, or that the total application of TCP was greater. Although the results of 1983 Hawaii State Department of Agriculture soil tests generally indicate that at greater depths residual concentrations of TCP are higher than DBCP or EDB, Mink (pers. commun., 1985) suggests that the greater extent and abundance of TCP in the ground water may reflect its earlier use. This implies that DBCP and perhaps EDB may eventually exhibit greater spatial extent and higher concentrations.

A general pattern may be discerned in the spatial distributions of the detected concentrations of DBCP and TCP. With the exception of the Del

Table 3. Pipeline Leaks in Southern Oahu

| Leak No. | Year | AVGAS loss (m^3) |
|----------|---------|----------------------|
| 1 | 1954 | 260 |
| 2 | 1978 | *190 |
| 3 | 1957-58 | 60 |
| 4 | 1954 | 80 |
| 5 | 1954 | 330 |
| 6 | 1954 | 1140 |
| 7 | 1955 | 60 |
| 8 | 1951 | 40 |
| 9 | 1954 | 80 |
| 10 | 1954 | 80 |

Source: Engineering-Science, 1984.

* JP-4 jet propulsion fuel.

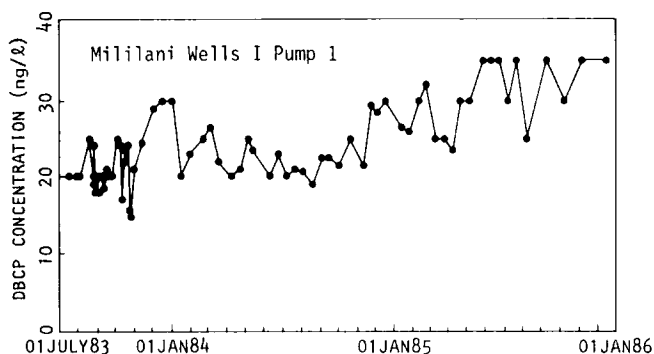


Fig. 8. Time series of DBCP concentration in Mililani Wells I Pump 1, Oahu, Hawaii.

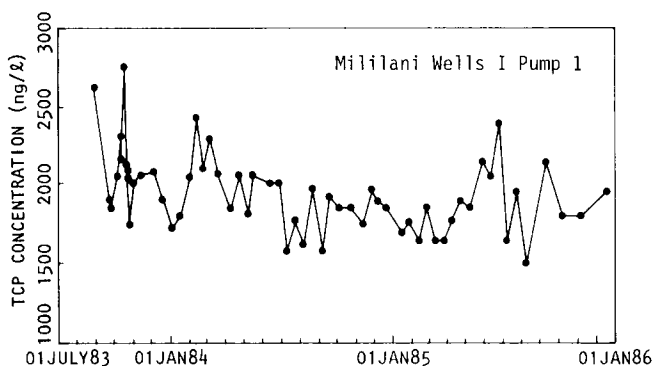


Fig. 9. Time series of TCP concentration in Mililani Wells I Pump 1, Oahu, Hawaii.

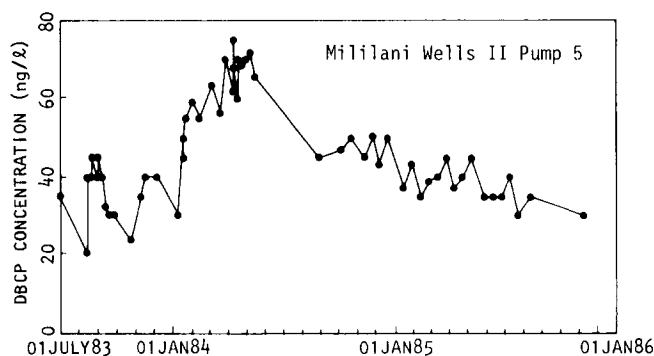


Fig. 10. Time series of DBCP concentration in Mililani Wells II Pump 5, Oahu, Hawaii.

Monte Kunia Well, concentrations are generally highest in wells located within the wetter pineapple fields and lower downgradient toward the drier northern and southern coasts of the island. Dividing the region along the 1000-mm (40-in.) median annual isohyet [corresponding to a 634-mm (25-in.) annual recharge rate for pineapple (Giambelluca, 1986)], maximum concentrations of DBCP in contaminated wells range from 2 to 43 ng/l in dry areas, and from 20 to 115 ng/l in wet areas. Similarly, maximum detected levels of TCP are in the 210- to 1100-ng/l range for areas with less than 1000 mm (40 in.) of rainfall, while maximum values of 430 to 2900 ng/l are found above

the 1000-mm (40-in.) isohyet. Although they may be due in part to differences in travel distance from upgradient sources of contamination, these observations underline the importance of the local recharge rate in nonpoint source contamination processes. Assessment of ground-water contamination risk from agrochemicals in Hawaii must be made with attention to site-specific climatic, edaphic, and geologic characteristics which influence chemical pathways in the environment.

Temporal Variation of Contamination

To examine temporal trends, contamination time series were constructed. Multiple tests on the same day were averaged, and only quantitated results were included. Figures 8 through 11 depict DBCP and TCP concentrations in Mililani Wells I Pump 1 and Mililani Wells II Pump 5. The Mililani Wells I site supplies water to the residents of Mililani and was pumped throughout the period from July 1, 1983 to January 1, 1986 at a rate of approximately 0.1 to 0.2 m³/s (2 to 4 million gallons per day). The Mililani Wells II site was pumped only sparingly between July 1, 1983 and January 1, 1986: 235 m³ (62,000 gal) were pumped during September 1984, and 30 m³ (8000 gal) were pumped during November 1985. EDB and TCP concentrations in Waipahu Wells Pump 4 are shown in Figures 12 and 13. The Waipahu Well site has not been pumped since August 1983 except to collect water samples. No analyses for DBCP, EDB, or TCP have been performed on water samples from the Waipahu site since January 1985. The data presented in Figures 8 through 13 are generally representative of the other wells in each field.

Based on the data presented in Figures 8 through 13 and on data of other pumps at the same sites, the following observations are tentatively offered regarding the temporal trends in contaminant concentrations. DBCP is increasing at Mililani Wells I. Further upgradient, in a higher

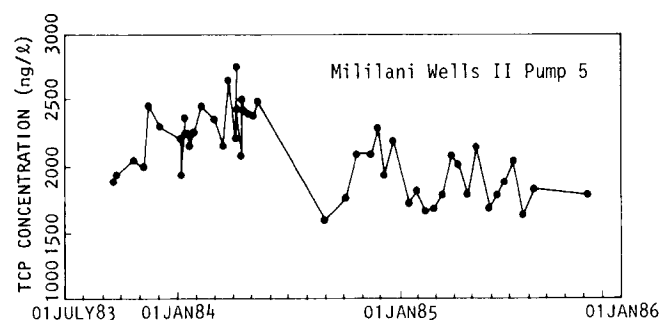


Fig. 11. Time series of TCP concentration in Mililani Wells II Pump 5, Oahu, Hawaii.

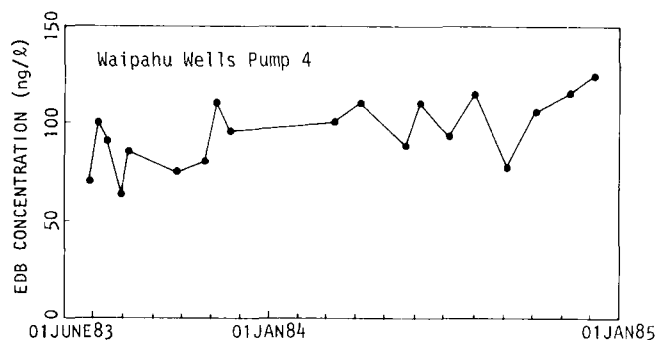


Fig. 12. Time series of EDB concentration in Waipahu Wells Pump 4, Oahu, Hawaii.

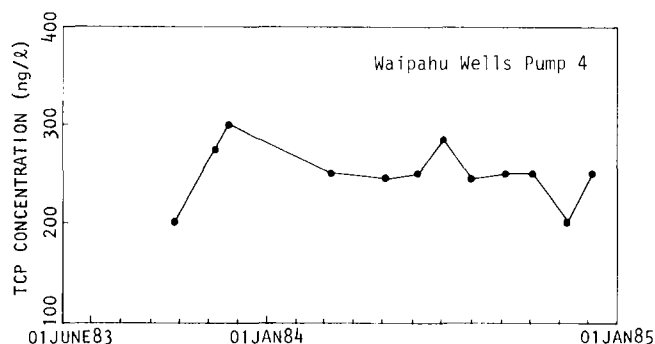


Fig. 13. Time series of TCP concentration in Waipahu Wells Pump 4, Oahu, Hawaii.

rainfall area, DBCP concentration at Mililani Wells II increased prior to March 1984 and has been declining thereafter. The differences in the time series for these two sites may be indicative of variations in recharge and timing of chemical applications. TCP at all three sites appears to be declining in concentration, although the trend at Waipahu Wells is nearly zero. EDB at Waipahu Wells is apparently increasing. Increasing levels of EDB at Waipahu and decreasing concentrations of TCP at all sites are consistent with the fact that use of DD (containing TCP) was begun and discontinued earlier than EDB.

Quantification of the temporal patterns of contaminant concentration by traditional statistical techniques, such as linear or polynomial least-squares, was not possible because of the presence of autocorrelation in the data (samples not independent). Lack of a regular sampling interval prevented the use of time-series analysis.

It should be emphasized that statements regarding temporal trends in contaminant concentrations are based on a very limited sample period and, as new data become available, apparent trends may prove to be part of short-term variability. Furthermore, the data on which these observations are based are subject to a large number of error sources from sampling, testing, and data reduction.

CONCLUSIONS

On the basis of existing well-water contamination data in Hawaii, the following tentative conclusions regarding DBCP, EDB, and TCP are suggested.

1. DBCP and TCP contamination of ground water on Oahu is derived from nonpoint and/or point sources associated with nematicide use in pineapple cultivation.
2. EDB may have entered the ground water as a result of the use and handling of the nematicide by pineapple plantations. Due to the presence of fuel pipeline leaks in the vicinity of the contamination, however, the source of EDB contamination cannot be identified with certainty.
3. The greater spatial extent and higher concentrations of TCP are indicative of its greater persistence and earlier use as compared with DBCP and EDB.
4. Areas on Oahu with greater than 1000 mm (40 in.) median annual rainfall are prone to much higher levels of ground-water contamination by agrochemicals than drier areas.
5. The direction of temporal trends in DBCP concentration at present varies according to site.
6. EDB concentration in the contaminated portion of the Pearl Harbor aquifer appears to be increasing at present.
7. TCP concentration in Oahu well water appears to be declining.

This paper represents a preliminary investigation of the spatial and temporal aspects of DBCP, EDB, and TCP contamination of Hawaii's ground waters. Future areas of study will include an analysis of soil boring data, an estimate of percolation rate and its effects on the fate of pesticide residues, and an examination of possible mitigation strategies for contaminated aquifers. To alleviate the water-supply problem created by the well closings, the Honolulu Board of Water Supply has opted to install activated carbon filtration units at three of the closed well sites. Filtration units were placed on line in March and May 1986, respectively at Mililani Wells I and Kunia Wells II, and are currently (February 1987) being installed at the Waipahu Wells.

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REFERENCES

- American Water Works Association. 1985. Update, date-line: Washington, D.C. American Water Works Association Journal. v. 77, pp. 16a-16b.
- Anderson, B. S. 1986. Public health and risk considerations. Paper presented to Toxic Chemicals in Hawaii Water Resources Workshop, January 14-15, 1986, College of Tropical Agriculture and Human Resources, University of Hawaii at Manoa, Honolulu, Hawaii.
- Carter, W. 1954. Dichloropropane-dichloropropene mixtures of different composition as soil fumigants in pineapple land. Journal of Economic Entomology. v. 47, no. 6, pp. 1101-1103.
- Cohen, S. Z., S. M. Creeger, R. F. Carsel, and C. G. Enfield. 1984. Potential for pesticide contamination of ground water resulting from agricultural uses. In: R. F. Krueger and J. N. Seiber (editors), Treatment and Disposal of Pesticide Wastes. American Chemical Society Symposium Series no. 259, pp. 297-325.
- Cohen, S. Z., C. Eiden, and M. N. Lorber. 1986. Monitoring ground water for pesticides in the USA. In: Evaluation of Pesticides in Ground Water. American Chemical Society Symposium Series no. 315.
- Department of Agriculture. 1983. Preliminary report on soil sampling for EDB on Oahu. Pesticides Branch, Division of Plant Industry, State of Hawaii, Honolulu, Hawaii. 19 pp. + appendices.
- Department of Agriculture. 1984. Chemical composition of Shell D-D soil fumigant. State of Hawaii, Honolulu, Hawaii. 1 p.
- Eckern, P. C. 1965. Evapotranspiration of pineapple in Hawaii. Plant Physiology. v. 40, no. 4, pp. 736-739.
- Engineering-Science. 1984. Installation restoration program phase I: Records search—15th ABW Satellite Installations, Hawaii. Report prepared for United States Air Force AFESC/DEV Tyndall AFB, Florida and HQ PACAF/DEEV Hickam AFB, Hawaii, variously paged.
- Eyre, P. R. 1983. The effects of pumpage, irrigation return, and regional ground-water flow on the water quality at Waiawa water tunnel, Oahu, Hawaii. U.S. Geological Survey, Honolulu, Hawaii. Water Resources Investigations Report 83-4097. 44 pp.
- Giambelluca, T. W. 1986. Land use effects on the water balance of a tropical island. National Geographic Research. v. 2, no. 2, pp. 125-151.
- Lau, L. S. 1985. Subsurface water quality: Organic chemical contamination of Oahu groundwater. Water Resources Research Center, University of Hawaii at Manoa, Honolulu, Hawaii. Special Report 7.0:85. 147 pp.
- Mink, J. F. 1980. State of the groundwater resources of southern Oahu. Board of Water Supply, City and County of Honolulu, Hawaii. 83 pp.
- Mink, J. F. 1981. DBCP and EDB in soil and water at Kunia, Oahu, Hawaii. Report prepared for Del Monte Corporation, Honolulu, Hawaii. 48 pp. + appendices.
- Mink, J. F. and S. T. Sumida. 1984. Aquifer classification, state of Hawaii. Water Resources Research Center, University of Hawaii at Manoa, Honolulu, Hawaii. Technical Memorandum Report no. 75. 34 pp.
- Munnecke, D. E. and S. D. Van Gundy. 1979. Movement of fumigants in soil, dosage responses, and differential effects. Annual Review of Phytopathology. v. 17, pp. 405-429.
- Oki, D. S. and T. W. Giambelluca. 1985. Subsurface water and soil quality data base for state of Hawaii. Water Resources Research Center, University of Hawaii at Manoa, Honolulu, Hawaii. Special Report 7:85. 92 pp.
- Rosenau, J. C., E. R. Lubke, and R. H. Nakahara. 1971. Water resources of north-central Oahu, Hawaii. U.S. Geological Survey, Washington, D.C. Geological Survey Water-Supply Paper 1899-D. 40 pp.
- Spencer, E. Y. 1982. Guide to the Chemicals Used in Crop Protection. 7th ed. Agriculture Canada Research Branch, Ontario, Canada. Publication 1093. 595 pp.
- Takasaki, K. J. 1977. Elements needed in design of a ground-water-quality monitoring network in the Hawaiian Islands. U.S. Geological Survey, Washington, D.C. Geological Survey Water-Supply Paper 2041. 23 pp.
- U.S. Department of Health and Human Services and U.S. Department of Labor. 1978. Occupational Health Guideline for 1,2,3-Trichloropropane. 4 pp.
- U.S. Environmental Protection Agency. 1980. 1,2,3-Trichloropropane health and environmental effects. Carcinogen Assessment Group, Office of Health and Environmental Assessment, Office of Research and Development, Washington, D.C., No. 169 in Carcinogen Assessment Group List of Carcinogens, April 30, 1980. 7 pp.
- U.S. Environmental Protection Agency. 1983. Ethylene dibromide; decision and emergency order suspending registrations of pesticide products containing ethylene dibromide for use as a soil fumigant. Federal Register. v. 48, pp. 46228-46248.
- Worthing, C. R. (editor). 1979. The Pesticide Manual: A World Compendium. 6th ed. British Crop Protection Council, Nottingham, England. 655 pp.
- Yim, S. K. and G. L. Dugan. 1975. Quality and quantity of nonpoint pollution sources in rural surface water runoff on Oahu, Hawaii. Water Resources Research Center, University of Hawaii at Manoa, Honolulu, Hawaii. Technical Report No. 93. 60 pp.

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